The f_{D_s} Puzzle

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Beyond the Standard Model:
From the Tevatron to the LHC
Fermilab, September 15–19

based on (and extending) Dobrescu & ASK,
PRL **100,** 241802 (2008) [arXiv:0803.0512 [hep-ph]]

Outline

- Conventional wisdom

- The f_{D_s} puzzle

- New physics: W', charged Higgs, leptoquarks

- Semileptonic decays

- Conclusions

Leptonic Decay

- Standard branching fraction for $D_s \to l\nu$ is

$$B(D_s \to \ell\nu) = \frac{m_{D_s}\tau_{D_s}}{8\pi} f_{D_s}^2 \left| G_F V_{cs}^* m_\ell \right|^2 \left(1 - \frac{m_\ell^2}{m_{D_s}^2} \right)^2$$

where the decay constant f_{D_s} is defined by

$$\langle 0 | \bar{s}\gamma_\mu\gamma_5 c | D_s(p) \rangle = i f_{D_s} p_\mu$$

- Usually experiments quote f_{Ds}.

Semileptonic Decay

- Standard differential rate for $D \to K\mu\nu$ is

$$\frac{d\Gamma}{dq^2} = \frac{m_D^3 G_F^2 |V_{cs}|^2}{192\pi^2} \left[\mathtt{PS}_+ |f_+(q^2)|^2 + \frac{m_\mu^2}{m_D^2} \mathtt{PS}_0 |f_0(q^2)|^2 \right]$$

where the form factors are defined by

$$\langle K(k)|\bar{s}\gamma^\mu c|D(p)\rangle = (p+k)_\perp^\mu f_+(q^2) + q^\mu f_0(q^2),$$

and $q \cdot (p+k)_\perp = 0$.

- Experiments quote either $|V_{cs}|$ or $f_+(0)$.

- Standard decay amplitudes are tree-level, W-mediated.

- Non-Standard amplitudes would have to be large to be noticeable.

- Non-Standard models are *popular* only if they are *predictive*, hence *constrained*.

- New physics is implausible, so $hl\nu$ are used to determine CKM, and $l\nu$ to test latQCD.

But something funny happened ...
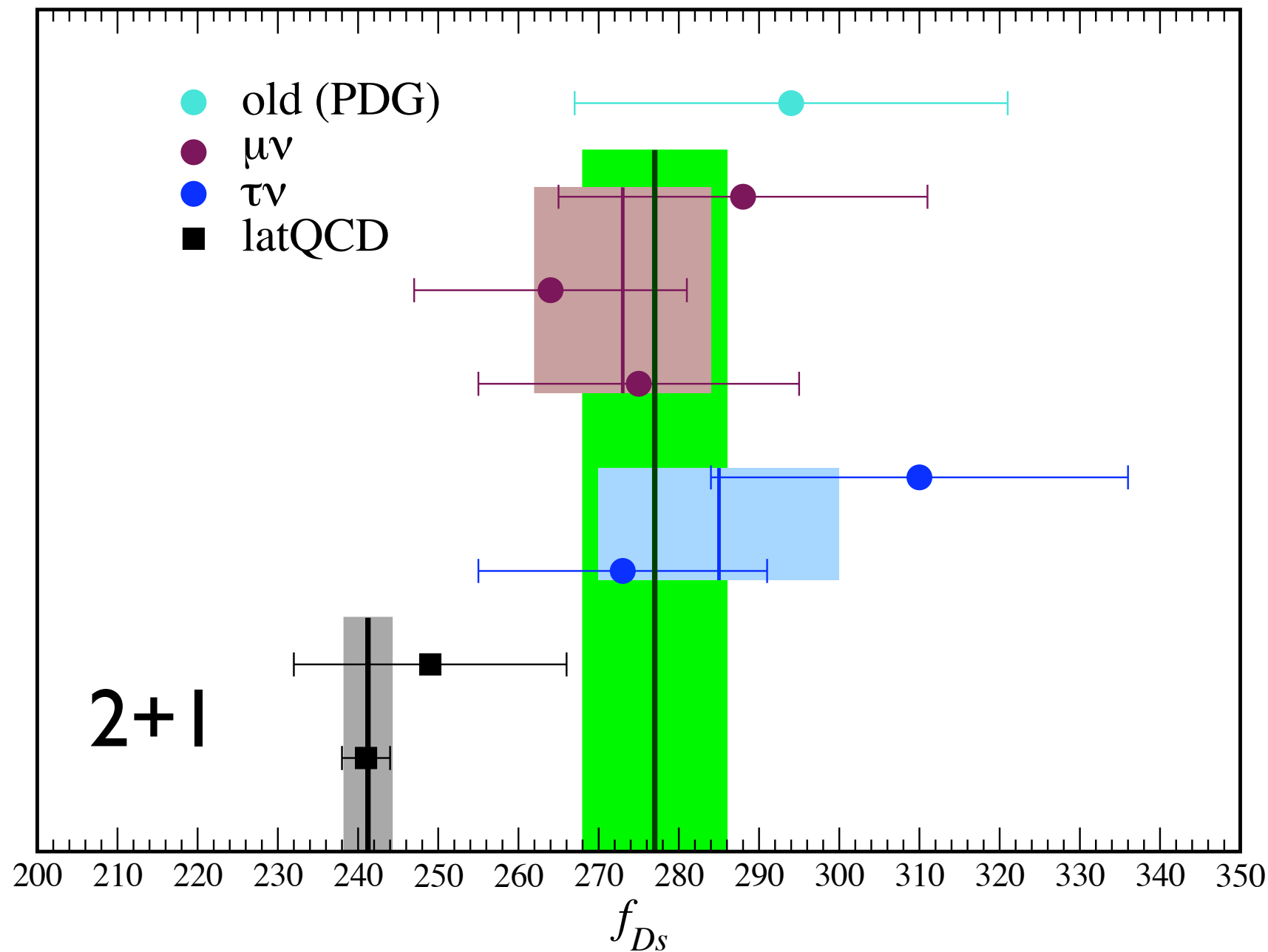
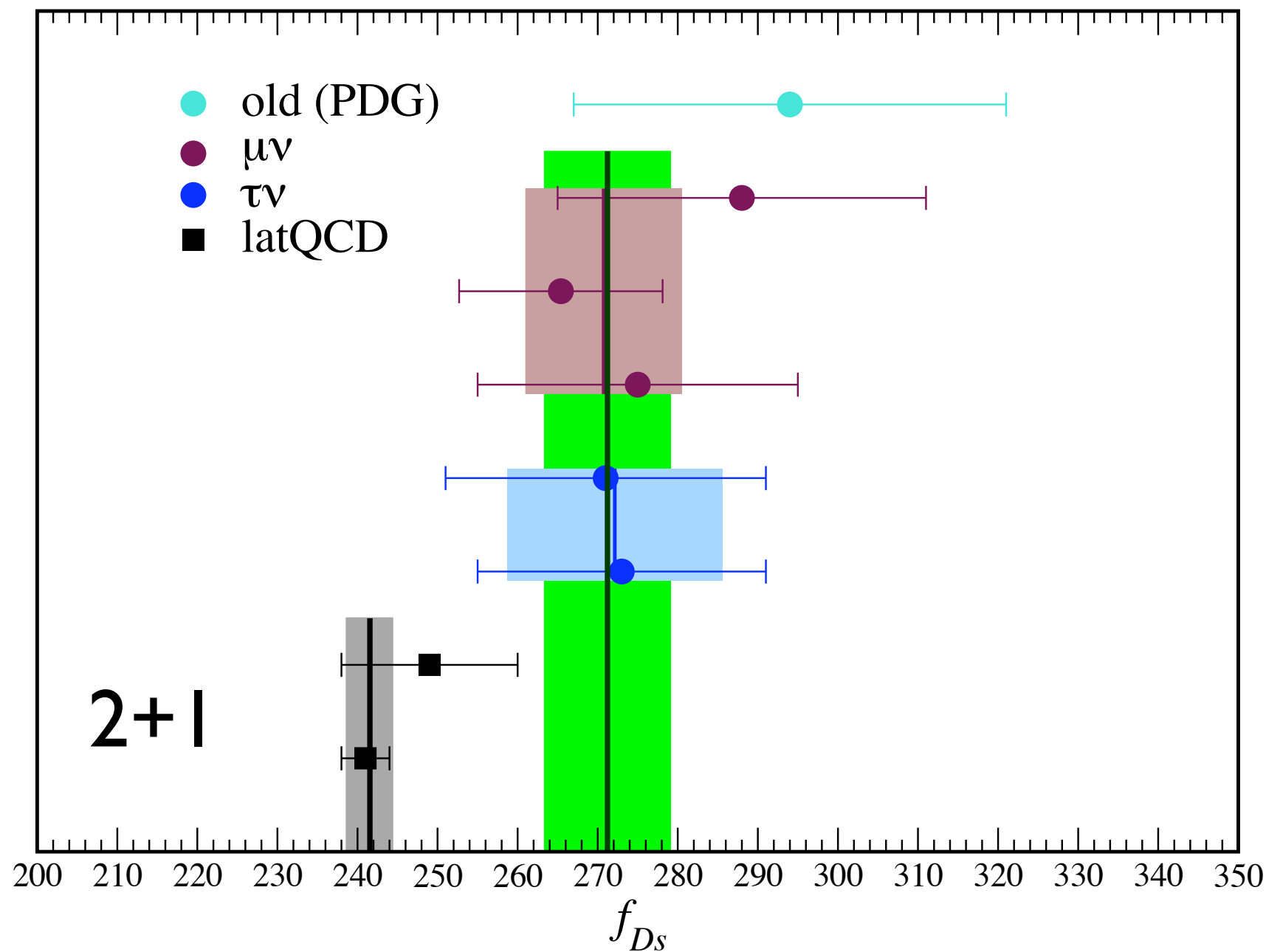$\chi^2/\text{dof} = 0.67$

BaBar
CLEO
Belle

CLEO $\pi\nu$
CLEO e$\nu\nu$
Fermilab/MILC
HPQCD

a 3.8σ discrepancy, or $2.7\sigma \oplus 2.9\sigma$.

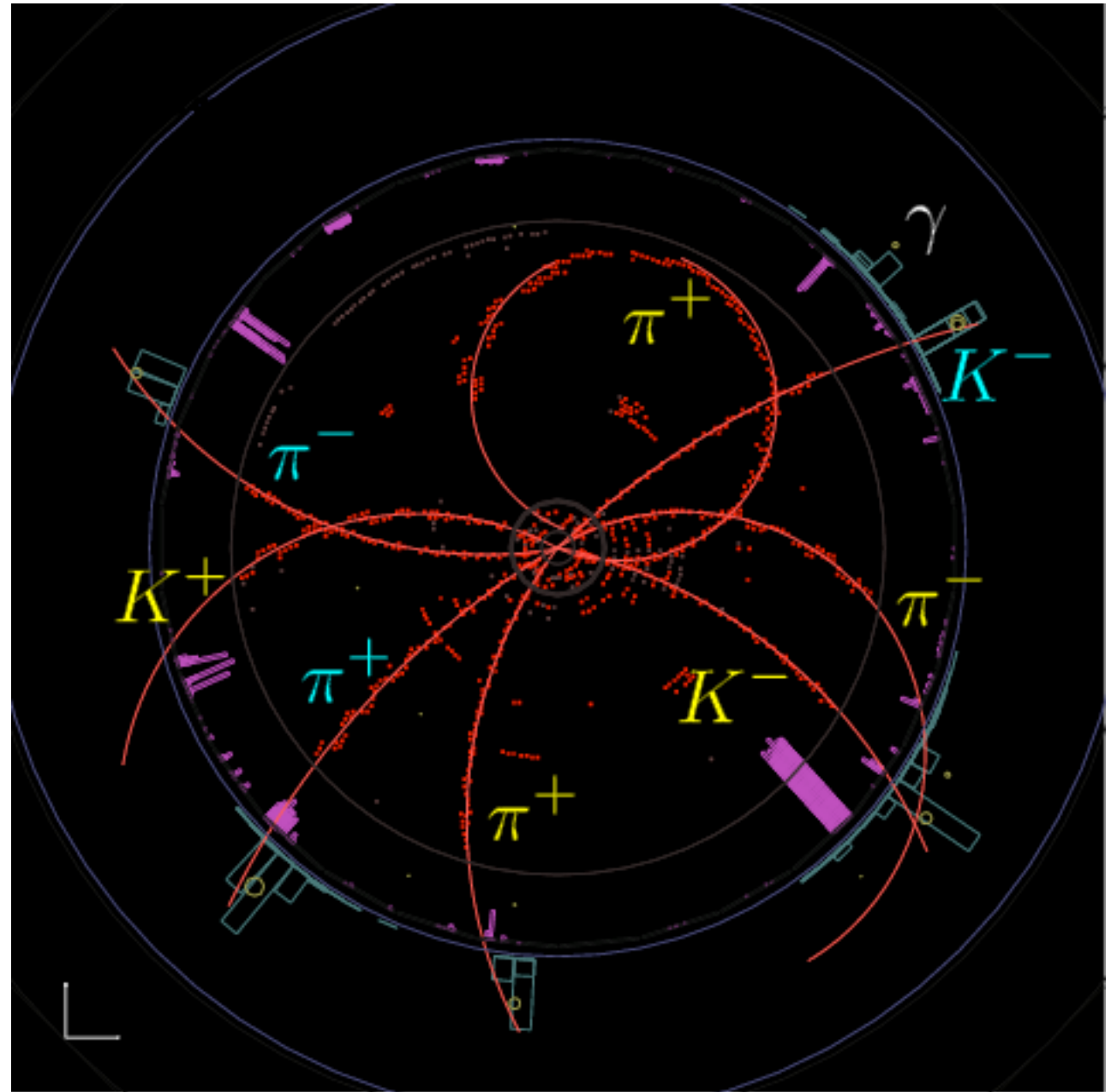# With CLEO's (our) update from FPCP (Lat08)...

$\chi^2/\text{dof} = 0.13$

BaBar
CLEO
Belle

CLEO $\pi\nu$
CLEO $e\nu\nu$
Fermilab/MILC
HPQCD

Legend:
- old (PDG)
- $\mu\nu$
- $\tau\nu$
- latQCD

2+1

f_{Ds}

a 3.5σ discrepancy, or $2.9\sigma \oplus 2.2\sigma$.

Experiments

- Measurements by BaBar, CLEO, Belle do not depend on models* for interpretation of the central value or the error bar.

- CLEO and Belle have absolute $B(D_s \to l\nu)$.

- Hard to see a misunderstood systematic.

- Could all fluctuate high?

- * except the Standard Model!

Last CLEO-c Event

$$e^+ e^- \rightarrow D_s^{*+} D_s^-$$

$$\downarrow \qquad \searrow$$

$$\gamma D_s^+ \qquad K^- K_S \rightarrow K^- \pi^+ \pi^-$$

$$\searrow$$

$$K^+ K^- \pi^+ \pi^+ \pi^-$$

CKM

- Experiments take $|V_{cs}|$ from 3-generation unitarity, either with PDG's global CKM fit or setting $|V_{cs}| = |V_{ud}|$. No difference.

- Even n-generation CKM requires $|V_{cs}| < 1$; would need $|V_{cs}| > 1.1$ to explain effect.

Radiative Corrections

- Fermi constant G_F from muon decay, so its radiative corrections implicit in $\mu\nu$ and $\tau\nu$.

- Standard treatment [Marciano & Sirlin] has a cutoff, set (for f_π) to m_ρ. Only 1–2%.

- More interesting is $D_s \longrightarrow D_s^* \gamma \longrightarrow \mu\nu\gamma$, which is *not* helicity suppressed. Applying CLEO's cut 1% for $\mu\nu$ [Burdman, Goldman, Wyler].

- Only $9.3\ \mathrm{MeV}$ kinetic energy in $D_s \rightarrow \tau\nu$.

Elements of HPQCD

- Staggered valence quarks

  - HISQ (highly improved staggered quark) action;

  - discretization errors $O(\alpha_s a^2)$, $O(a^4)$;

  - absolutely normalization from PCAC;

  - less taste breaking;

  - tiny statistical errors: 0.5% on f_{Ds}.

- 2+1 rooted staggered sea quarks:

  - Lüscher-Weisz gluon + asqtad action;

  - discretization errors $O(\alpha_s a^2)$, $O(a^4)$;

  - discretization errors cause small violations of unitarity, controllable by chiral perturbation theory.

- Combined fit to a^2, m_{sea}, m_{val} dependence: not fully documented, but irrelevant for f_{Ds}.
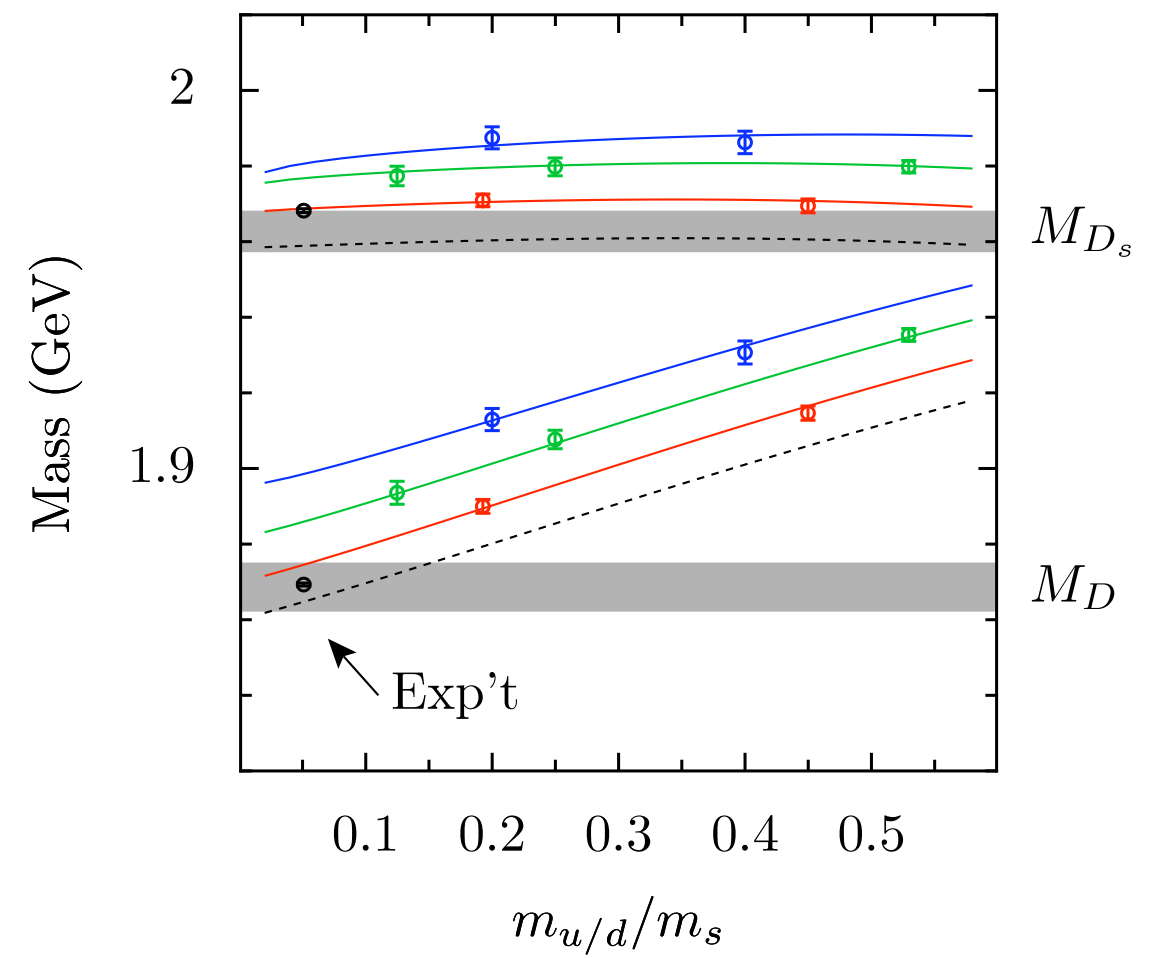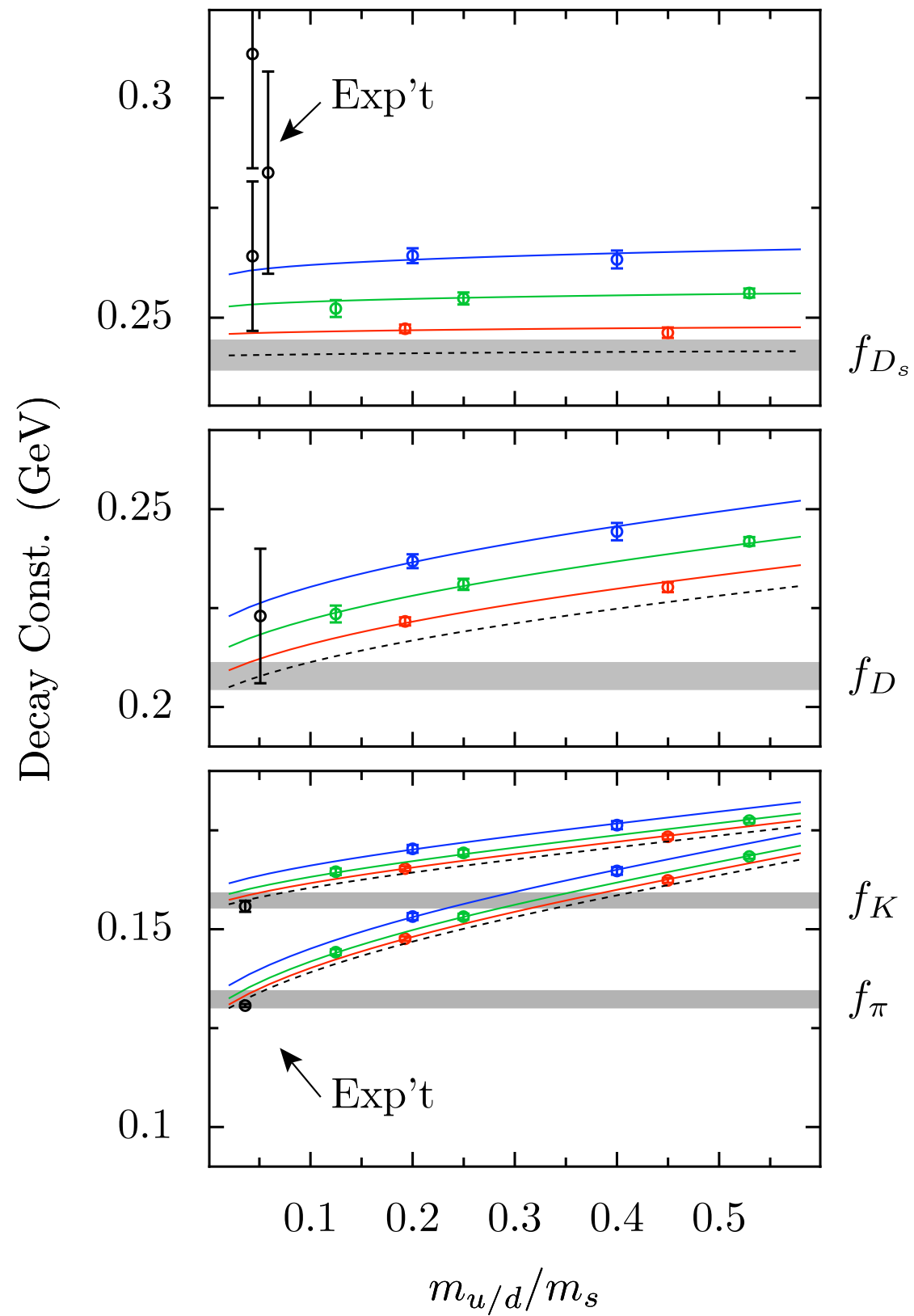
m_K and m_π set m_s, m_q
charmonium sets m_c
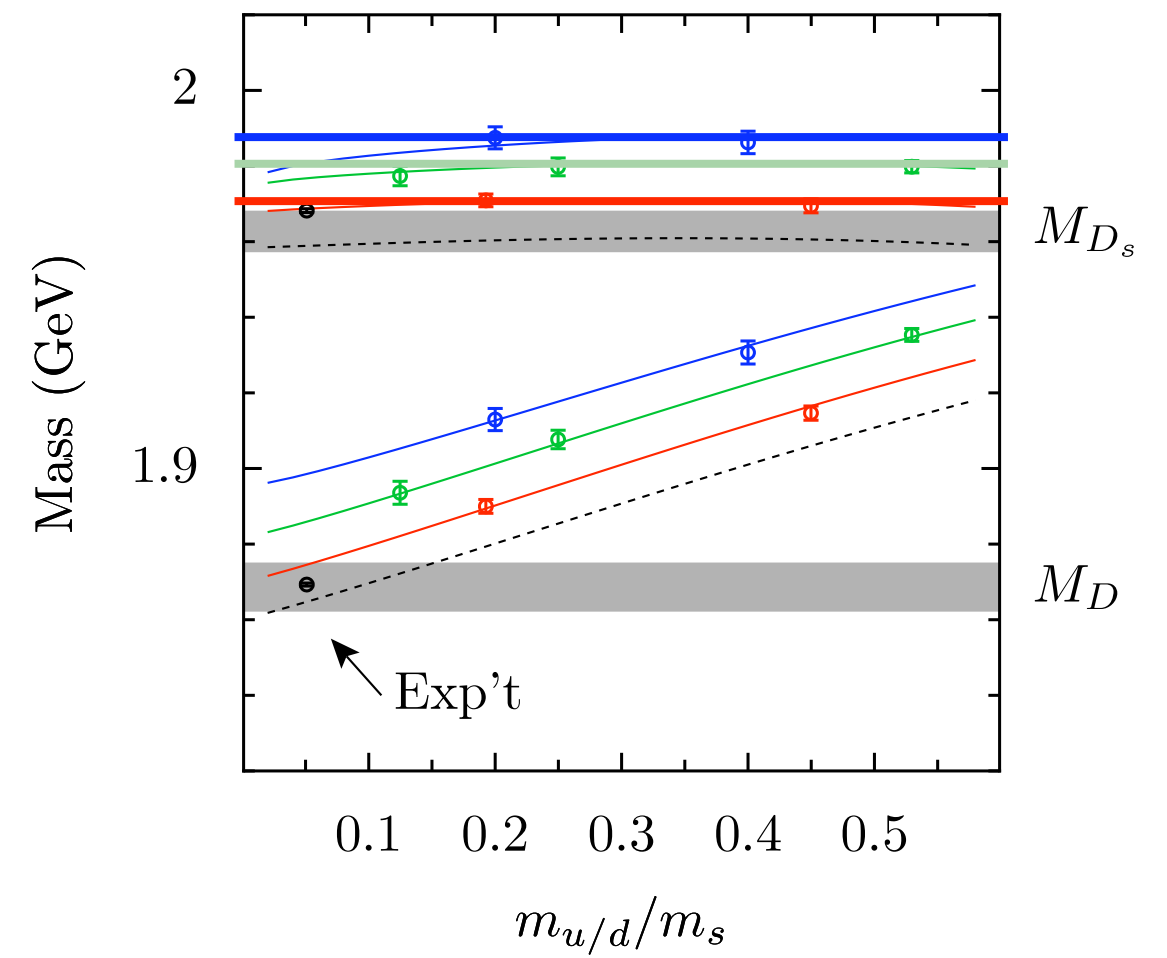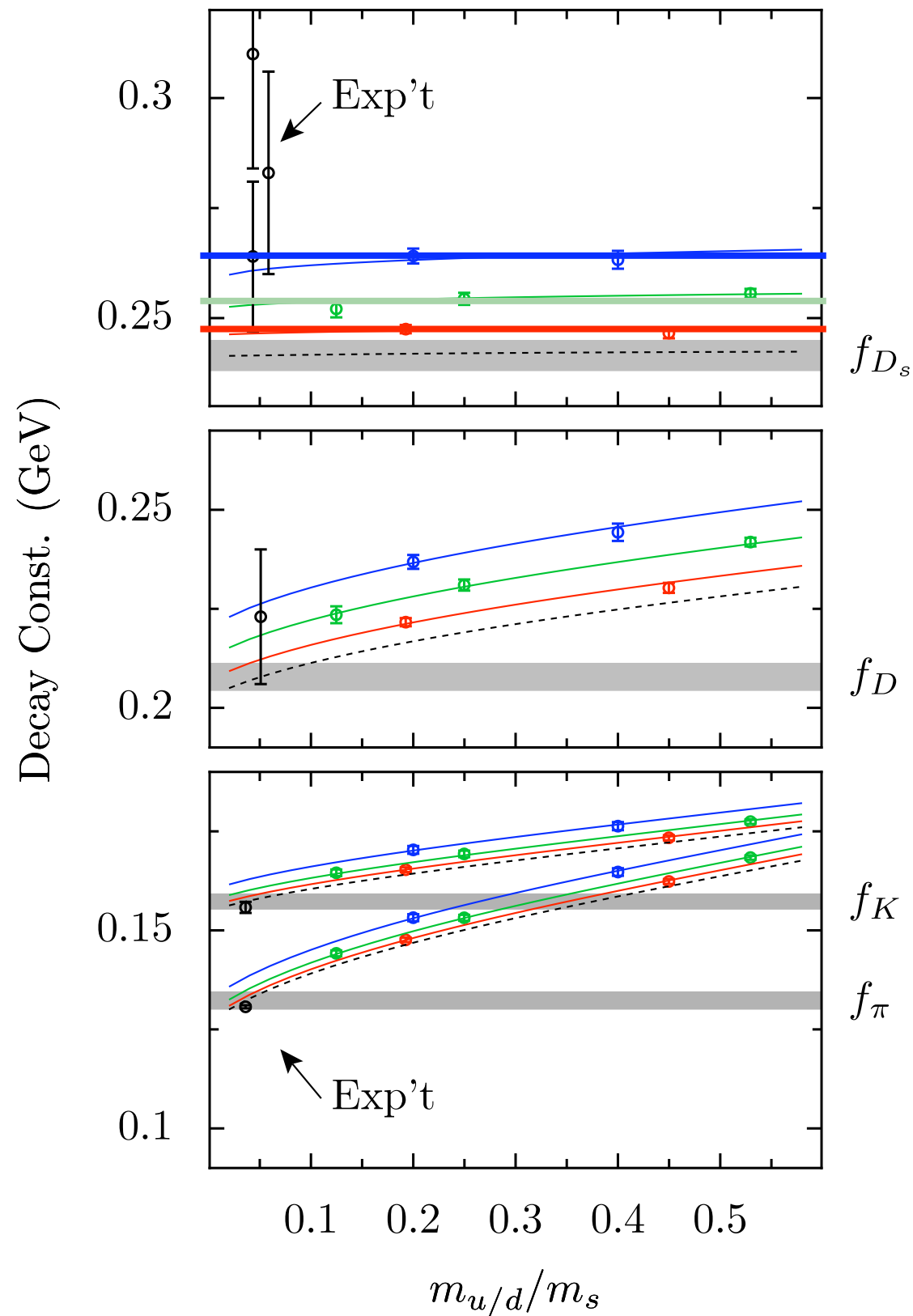
m_K and m_π set m_s, m_q
charmonium sets m_c

Assuming flat in m_{sea}.

As the lattice gets finer, the discrepancy grows:

271.2±7.9 MeV

slope is $O(\alpha_s m_c \Lambda a^2)$ as expected

HPQCD 241±3

linear in a^2: 239; quad in a^2: 242; linear in a^4: 245.
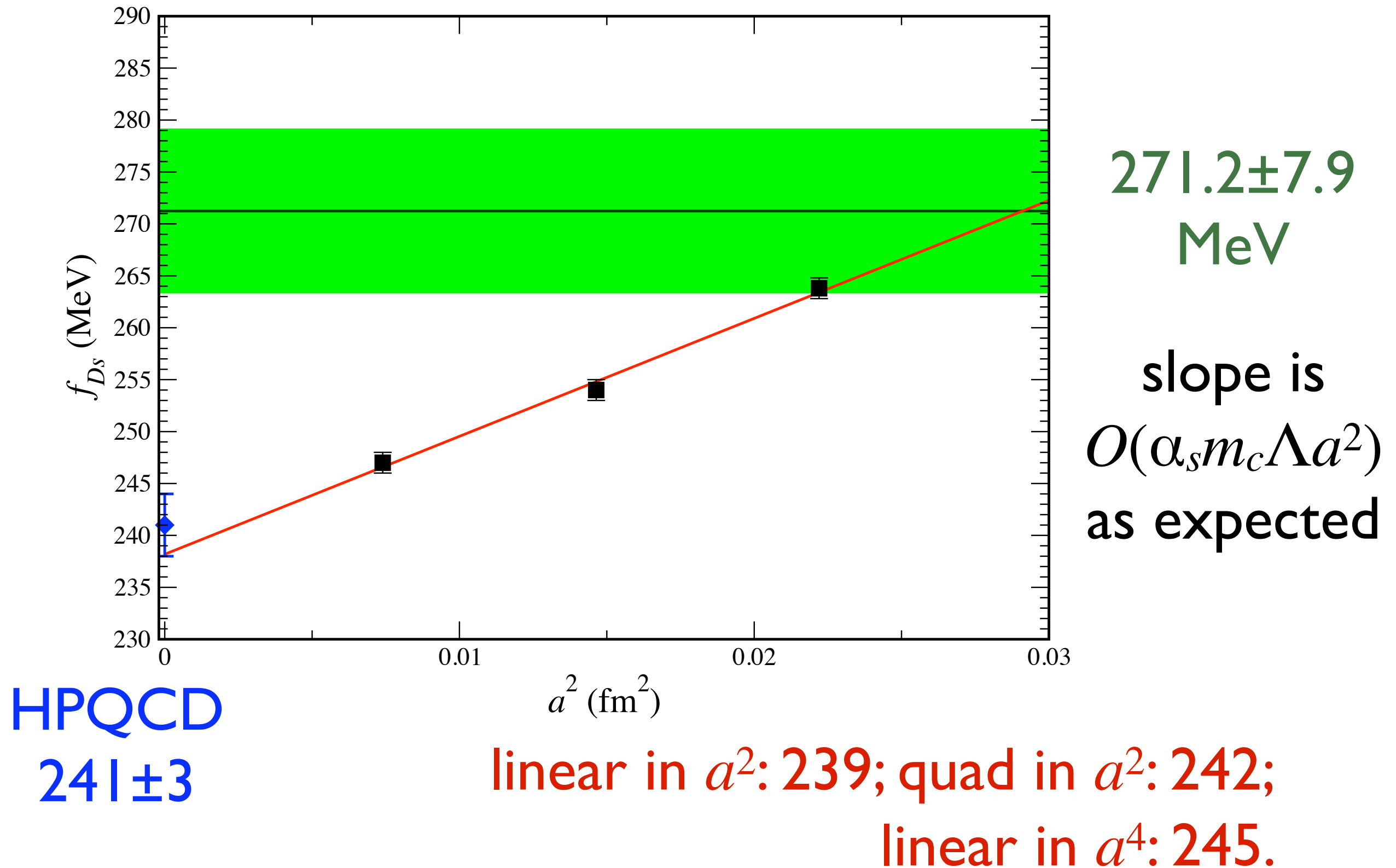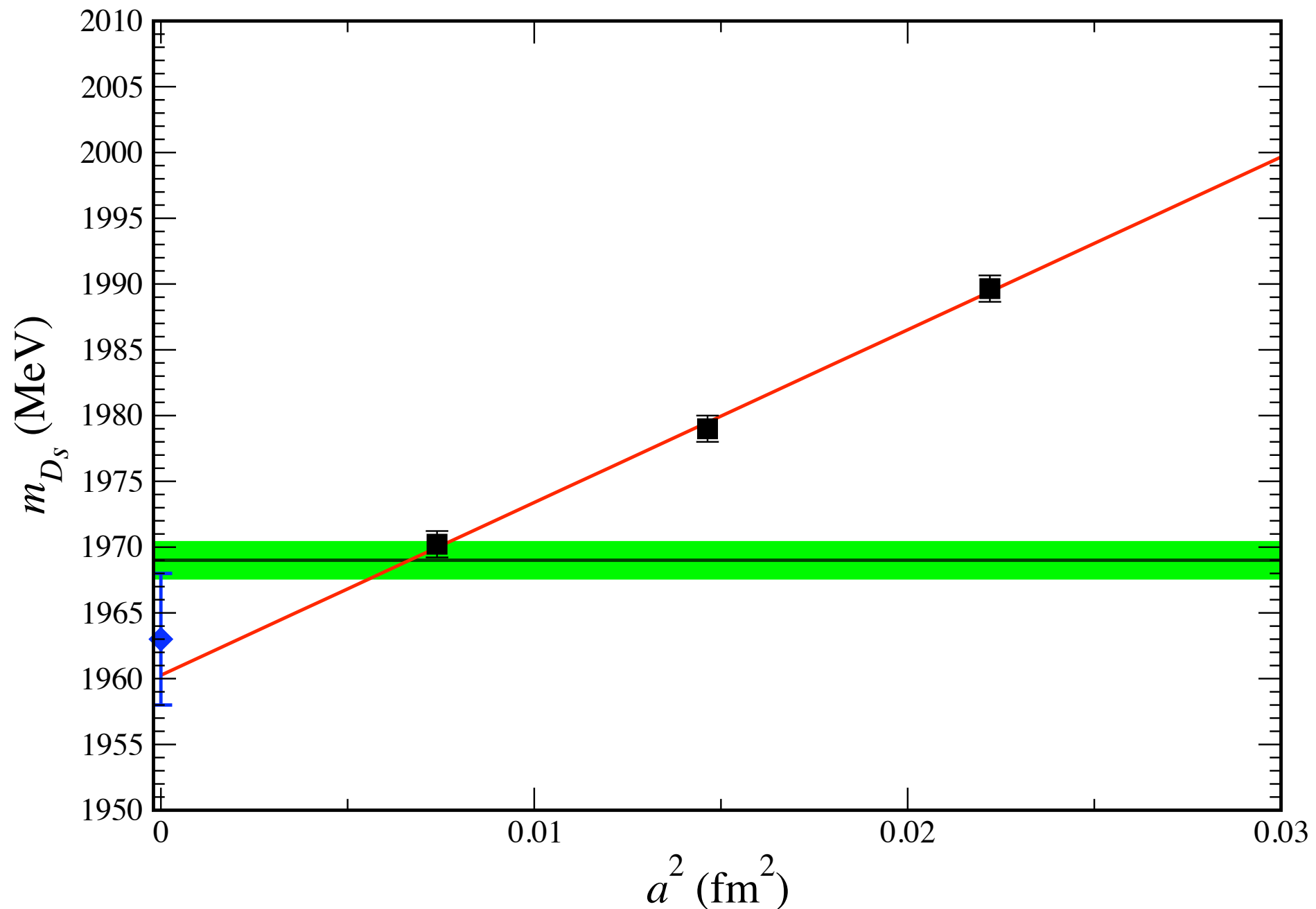
If m_c (set from η_c) were retuned to flatten this, f_{Ds} (at $a \neq 0$) would not change much.

Error Budget

$$\Delta_q = 2m_{Dq} - m_{\eta c}$$

	f_K/f_π	f_K	f_π	f_{D_s}/f_D	f_{D_s}	f_D	Δ_s/Δ_d
r_1 uncerty.	0.3	1.1	1.4	0.4	1.0	1.4	0.7
a^2 extrap.	0.2	0.2	0.2	0.4	0.5	0.6	0.5
Finite vol.	0.4	0.4	0.8	0.3	0.1	0.3	0.1
$m_{u/d}$ extrap.	0.2	0.3	0.4	0.2	0.3	0.4	0.2
Stat. errors	0.2	0.4	0.5	0.5	0.6	0.7	0.6
m_s evoln.	0.1	0.1	0.1	0.3	0.3	0.3	0.5
m_d, QED, etc.	0.0	0.0	0.0	0.1	0.0	0.1	0.5
Total %	0.6	1.3	1.7	0.9	1.3	1.8	1.2

charmed sea $\ll 1\%$?

Other Results

what	expt	HPQCD	
$m_{J/\psi} - m_{\eta c}$	118.1	111 ± 5‡	MeV
m_{Dd}	1869	1868 ± 7	MeV
m_{Ds}	1968	1962 ± 6	MeV
Δ_s/Δ_d	1.260 ± 0.002	1.252 ± 0.015	
f_π	130.7 ± 0.4	132 ± 2	MeV
f_K	159.8 ± 0.5	157 ± 2	MeV
f_D	205.8 ± 8.9*	207 ± 4	MeV

*CLEO new   ‡annihilation corrected

BSM

- If measurement, radiative corrections, and the SM calculation are in order ...

- ... the discrepancy could stem from non-Standard physics.

- How wacky could it be?

- It turns out particles that are already being considered can do the trick.

Effective Lagrangian

- The new particles will be heavy. Write

$$\mathcal{L}_{\text{eff}} = M^{-2}C_A^l(\bar{s}\gamma^\mu\gamma_5 c)(\bar{\nu}_L\gamma_\mu l_L) + M^{-2}C_P^l(\bar{s}\gamma_5 c)(\bar{\nu}_L l_R)$$
$$- M^{-2}C_V^l(\bar{s}\gamma^\mu c)(\bar{\nu}_L\gamma_\mu l_L) + M^{-2}C_S^l(\bar{s}c)(\bar{\nu}_L l_R)$$
$$+ M^{-2}C_T^l(\bar{s}\sigma^{\mu\nu}c)(\bar{\nu}_L\sigma_{\mu\nu}l_R)$$

  with left-handed neutrinos only.

- First two: leptonic; last three: semileptonic.

- Because V_{cs} has a small imaginary part (in PDG parametrization), to explain the effect one of C_A, C_P must be real and positive.

- To reduce each effect to 1σ,

$$\frac{M}{(\text{Re}\, C_A^\ell)^{1/2}} \lesssim \begin{cases} 710\,\text{GeV} & \text{for } \ell = \tau \\ 850\,\text{GeV} & \text{for } \ell = \mu \end{cases},$$

$$\frac{M}{(\text{Re}\, C_P^\ell)^{1/2}} \lesssim \begin{cases} 920\,\text{GeV} & \text{for } \ell = \tau \\ 4500\,\text{GeV} & \text{for } \ell = \mu \end{cases}.$$

New Particles

- The effective interactions can be induced by heavy particles of charge $+1$, $+2/3$, $-1/3$.
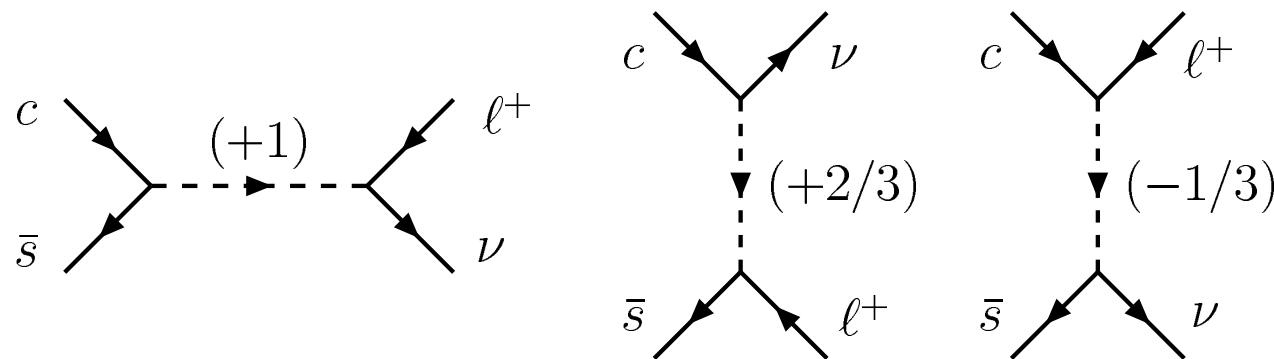
- Charged Higgs, new W'; leptoquarks.

Leptonic Decay

- In the amplitude, replace

$$G_F V_{cs}^* m_l \rightarrow G_F V_{cs}^* m_l + \frac{1}{\sqrt{2}M^2} \left(C_A^l m_l + \frac{C_P^l m_{D_s}^2}{m_c + m_s} \right)$$

so C_A can be l independent and still cause the same shift in both modes.

W'

- Contributes only to C_A and C_V.

- New gauge symmetry, but couplings to left-handed leptons constrained by other data.

- If W and W' mix, electroweak data imply it's too weak to affect $D_s \nrightarrow l\nu$.

- Seems unlikely, barring contrived, finely tuned scenarios.

Charged Higgs

- Multi-Higgs models include Yukawa terms

$$y_c \bar{c}_R s_L H^+ + y_s \bar{c}_L s_R H^+ + y_\ell \bar{\nu}_L^\ell \ell_R H^+ + \text{H.c.},$$

(mass-eigenstate basis) leading to

$$C_{P,S}^\ell = \tfrac{1}{2}\left(y_c^* \mp y_s^*\right) y_\ell, \qquad M = M_{H^\pm}$$

$$\propto V_{cs}^*(m_c \mp m_s \tan^2 \beta) m_\ell \quad \text{in Model II}$$

- Note that $C_{P,S}$ can have either sign.

- But consider a two-Higgs-doublet model

  - one for c, u, l, with VEV 2 GeV or so;

  - other for d, s, b, t, with VEV 245 GeV.

- No FCNC; CKM suppression.

- Need to look at one-loop FCNCs.

- Naturally has same-sized increase for μ & τ.

- This model predicts a similarly-sized deviation in $D \to l\nu$, so it is now disfavored:
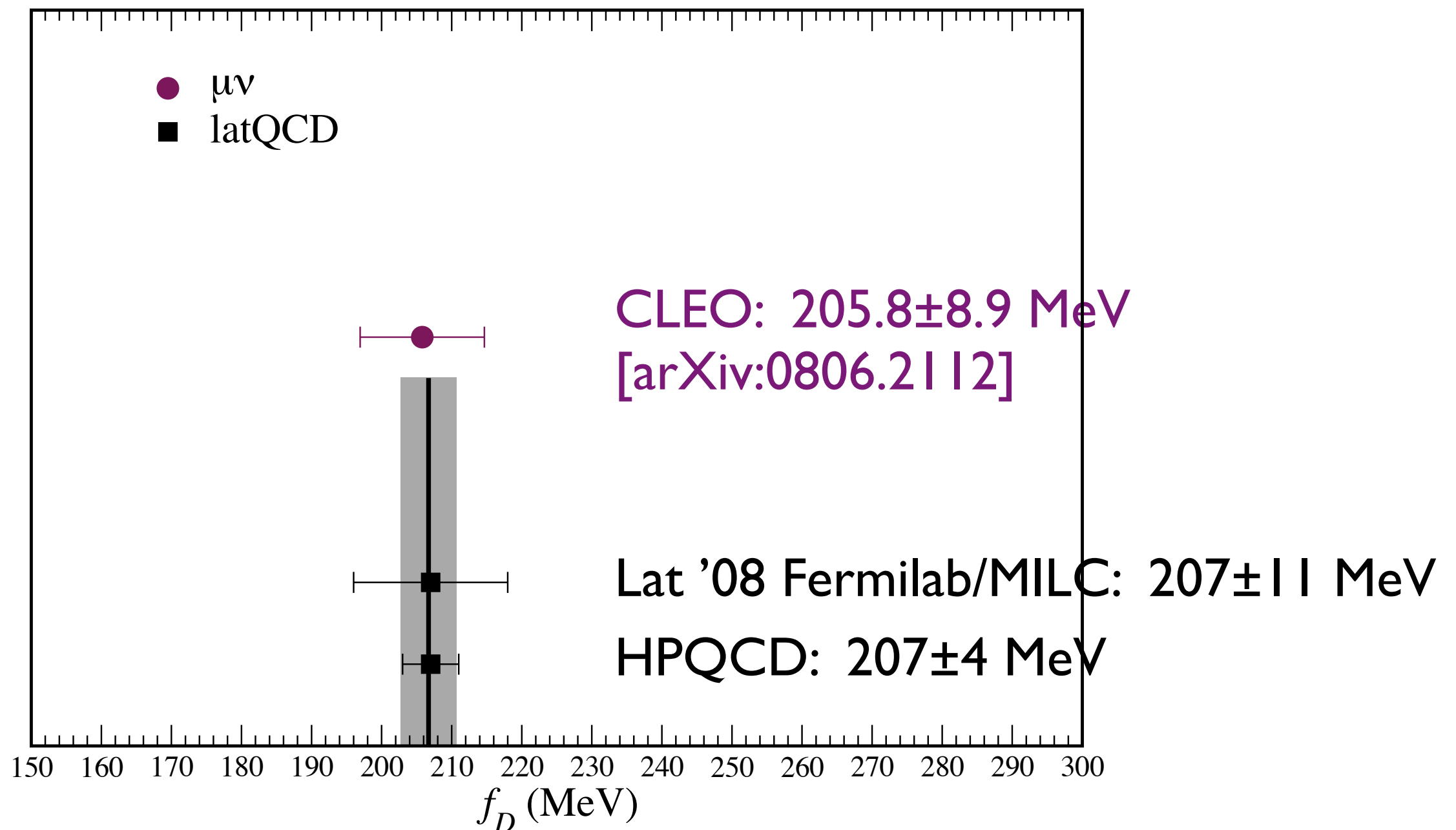
Leptoquarks

- Color triplet, scalar doublet with $Y = +7/6$ has a component with charge $Q = +2/3$.

- Dobrescu and Fox use this in a new theory of fermion masses [arXiv:0805.0822].

- Leads to $C_A = C_V = 0$, $C_P = C_S = 4C_T$ of any phase, and no connection between μ & τ.

- LFV $\tau \rightarrow \mu s \bar{s}$ disfavors this.

- LFV $\tau \to \mu s\bar{s}$ disfavors any leptoquark with a charge +2/3 component:

  - $J = 1$, $(3, 3, +2/3)$ and $(3, 1, +2/3)$

  - $J = 0$, $(3, 3, -1/3)$
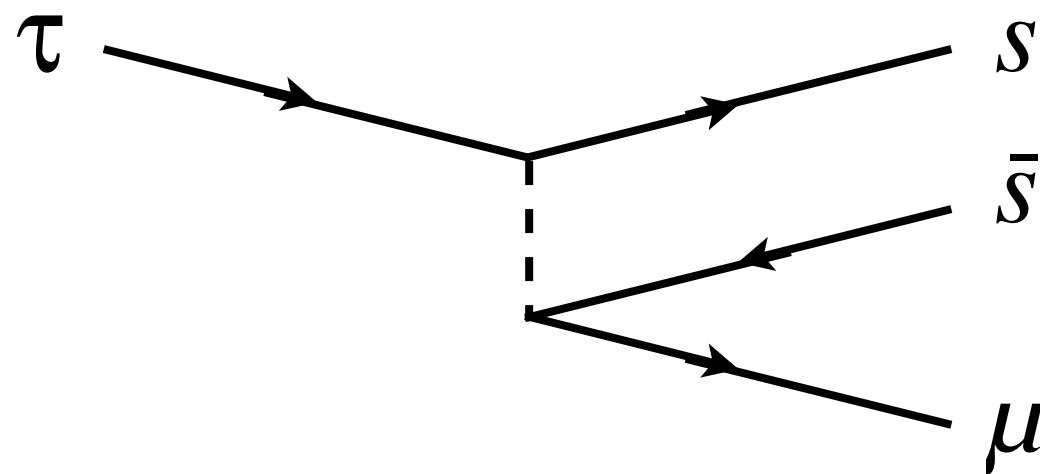
- Way out: two leptoquarks, little mixing.

- But $J = 0$, $(3, 1, -1/3)$ seems promising:

$$\kappa_\ell(\bar{c}_L \ell_L^c - \bar{s}_L \nu_L^{\ell c})\tilde{d} + \kappa_\ell' \bar{c}_R \ell_R^c \tilde{d} + \text{H.c.}$$

(an interaction in R-violating SUSY), with

$$C_A^\ell = C_V^\ell = \tfrac{1}{4}|\kappa_\ell|^2$$

$$C_P^\ell = C_S^\ell = \tfrac{1}{4}\kappa_\ell \kappa_\ell'^* = -2C_T^\ell$$

- If $|\kappa_\ell'/\kappa_\ell| \ll m_\ell m_c/m_{D_s}^2$, then *automatically* the interference is constructive and creates the same per-cent deviation for $\mu\nu$ and $\tau\nu$.

Semileptonic Decay

$$\frac{d\Gamma}{dq^2} = \frac{m_D^3}{192\pi^2} \left\{ \text{PS}_{++} |f_+(q^2)|^2 \left| G_F V_{cs} + \frac{C_V}{\sqrt{2}M^2} \right|^2 \right.$$

$$+ \text{PS}_{00} |f_0(q^2)|^2 \left| \frac{m_\mu}{m_D} \left(G_F V_{cs} + \frac{C_V}{\sqrt{2}M^2} \right) + \frac{q^2}{m_D(m_c - m_s)} \frac{C_S}{\sqrt{2}M^2} \right|^2$$

$$- \text{PS}_{T+} B_T(q^2) f_+(q^2) \frac{m_\mu}{4m_D} \text{Re}\left[\left(G_F V_{cs} + \frac{C_V}{\sqrt{2}M^2} \right) \frac{C_T^*}{\sqrt{2}M^2} \right]$$

$$\left. - \text{PS}_{T0} B_T(q^2) f_0(q^2) \frac{m_\mu}{4m_D} \text{Re}\left[\left(G_F V_{cs} + \frac{C_V}{\sqrt{2}M^2} \right) \frac{C_T^*}{\sqrt{2}M^2} \right] \right\}$$

- C_V causes an effect comparable to $l\nu$, but C_S and C_T could hide: $m_\mu/m_D = 0.057$

Measuring $D \to K\mu\nu$

- Effective couplings in semileptonic and leptonic decays are related.

- Observing SM rate for $D \to K\mu\nu$ would favor shift via C_P, w/ C_S & C_T shifts hiding.

- For leptoquarks implies the Yukawa matrix is "just so," to give $D \to \mu\nu$ & $D \to \tau\nu$.

- Observing excess in $D \to K\mu\nu$ would favor model with naturally same-sized effects in $D_s \to \mu\nu, \tau\nu$.

- Current status:

$$f_+(0) = 0.765(9) \quad \text{[CLEO]}$$
$$f_+(0) = 0.727(13) \quad \text{[BaBar]}$$
$$f_+(0) = 0.695(23) \quad \text{[Belle]}$$
$$f_+(0) = 0.747(7) \quad \text{[expt. avg.]}$$
$$f_+(0) = 0.73(8) \quad \text{[Fermilab/MILC]}$$

Leptoquarks

- Leptoquarks come with Yukawa matrices:

  - no relation between c and b couplings;

  - aesthetically unappealing.

- If a signal is real, aesthetics are a secondary problem.

- If coupling to 1st generation is small, these leptoquarks evade Tevatron bounds.

LHC

- The generic bounds on mass/coupling suggest that any non-Standard explanation of the effect is observable at the LHC.

- Charged Higgs: similar to usual search.

- Leptoquarks: $gg \to \tilde{d}\tilde{\bar{d}} \to \ell_1^+ \ell_2^- j_c j_c$, where leptons are μ or τ.

Perspective

- The f_{Ds} puzzle is intriguing.

- More calculations of f_{Ds} and form factors (f_+, f_0, and B_T) needed—

  - with n_f = 2+1 or 2+1+1.

- CLEO has more data to analyze.

- BES just started: D & D_s after ψ runs.